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Testing to Ensure Compliance with 1% Unexploded Ordnance (UXO) Limitations

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Testing to Ensure Compliance with 1% Unexploded Ordnance (UXO) Limitations

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Abstract

US law regarding cluster munitions prohibits the sale or transfer of technology, export license, or military assistance unless the submunitions do not result in more than 1% unexploded ordnance (UXO) across the range of intended operational environments. Multiple US allies want to upgrade their capabilities by licensing or otherwise using US technology to improve the performance of their cluster munitions systems. Testing is required to establish compliance with the 1% limit on UXO. Current Acquisition, Technology, and Logistics (AT&L) guidance requires that "a tailored test and evaluation approach is necessary to determine, with reasonable confidence, compliance with the requirement." This paper describes some historical approaches to developmental and operational testing in which one of the goals was munition reliability and demonstrates how variations of these approaches might be applied to meeting legal requirements in the UXO example. Related analyses isolate some of the pitfalls and risks inherent in testing and attempt to provide suggestions for best practices to support statute and guidance.

Introduction

An allied nation had a manufacturing license agreement (MLA) granted by the Department of State to produce rocket systems that included M77 submunitions (see Figure 1). The MLA expired in 2011. The ally desires to continue production of the submunition, using an indigenously developed self-destruct fuze (SDF) that will reduce the UXO rate to less than 1%, as required by US law. The Office of the Secretary of Defense (OSD) interprets the language in the law *(… the submunitions … do not result in more than 1% unexploded ordnance across the range of intended operational environments*) to require that the 1% threshold has to be met under all operating conditions.

Preliminary testing was conducted and assessed by the US Army in spring 2013 for various ranges and temperatures to explore performance over the operational environment. During this testing, the 1% threshold was met under some conditions but not others. The testing provided information on how the munitions should be employed and how they should be tested to ensure compliance with statute.

The ally has proposed a more extensive modified test to establish UXO rates more precisely. This paper describes the work done by Tactical Warfare Systems (TWS) and Developmental Test & Evaluation (DT&E) to assess the adequacy of the proposed test and determine passing criteria.

Figure 1. M77 Submunition

Cluster Bomb Unit (CBU)-105: A Precedent for Foreign Military Sales (FMS) of a Submunition System

The CBU-105 Sensor Fuzed Weapon (SFW) has been in development since the early 1990s, with several upgrades. The SFW dispenses 10 submunitions, each with 4 skeet warheads. See Figure 2. Over that time, the tested UXO rate on these warheads has dropped by an order of magnitude of around 5% to around 0.5%. The latest variant underwent 17 separate tests—primarily production verification tests—from 2002 until 2008. These tests yielded 3 duds classified as UXO out of 625 armed warheads. This testing, in conjunction with engineering analyses, was viewed as sufficient to determine compliance with the 1% UXO requirement**.** Retrospectively, we analyzed the combined data from these tests and found that a UXO rate of less than 1% was demonstrated with 87% confidence.

Figure 2. CBU-105 SFW

Initial Testing of the SDF and Lessons Learned

The SDF was tested at the White Sands Missile Range (WSMR) in spring 2013, using rockets carrying inert grenades. Three missions (four rockets each) were fired, one each at long (43.8), medium (34.6 km), and short (16.8 km) range. In addition, the potential impact of temperature conditioning was explored by conditioning at cold, ambient, and hot conditions. The effects of the range to target and the temperature of the munitions are routinely measured during the testing of munitions systems to ensure functionality across the operating environment.

Range-safety considerations constrained the short-range shots to a single impact point, precluding separation by temperature at that range. Further, two medium-range shots (one hot and one ambient) impacted too close together to determine the carrier of the submunitions. This situation confounded attempts to separate range and temperature effects.

The fuzes were the system under test, so inert grenades were used to simplify test conduct and scoring. Using inert grenades also eased the safety constraints, especially for clearance. However, premature detonation of a grenade in the air can cause the fuze failure of neighboring grenades, so potentially important failure modes were excluded. Despite these limitations, the resulting data (see Table 1) provided important insights.

Table 1. SDF Data from 2013 WSMR Testing

<table>
<tr><th>Mission</th><th>Range</th><th>Condition</th><th>Rockets</th><th>Loaded Submunitions</th><th>Recovered Submunitions</th><th>Total Number of UXO</th></tr>
<tr><td rowspan="4">SAT-1</td><td>43.8 km</td><td>Cold</td><td>1</td><td>504</td><td>503</td><td>0</td></tr>
<tr><td>43.8 km</td><td>Cold</td><td>1</td><td>504</td><td>487</td><td>0</td></tr>
<tr><td>43.8 km</td><td>Ambient</td><td>1</td><td>504</td><td>493</td><td>7</td></tr>
<tr><td>43.8 km</td><td>Ambient</td><td>1</td><td>504</td><td>504</td><td>6</td></tr>
<tr><td rowspan="4">SAT-2</td><td>34.6 km</td><td>Hot</td><td>1</td><td>504</td><td>498</td><td>1</td></tr>
<tr><td>34.6 km</td><td>Hot</td><td>1</td><td>504</td><td rowspan="2">993</td><td rowspan="2">9</td></tr>
<tr><td>34.6 km</td><td>Ambient</td><td>1</td><td>504</td></tr>
<tr><td>34.6 km</td><td>Ambient</td><td>1</td><td>504</td><td>498</td><td>0</td></tr>
<tr><td rowspan="4">SAT-3</td><td>16.8 km</td><td>Hot</td><td>1</td><td>504</td><td rowspan="4">1,993</td><td rowspan="4">38</td></tr>
<tr><td>16.8 km</td><td>Cold</td><td>1</td><td>504</td></tr>
<tr><td>16.8 km</td><td>Ambient</td><td>1</td><td>504</td></tr>
<tr><td>16.8 km</td><td>Ambient</td><td>1</td><td>504</td></tr>
</table>

Averaged over all shots, the system UXO rate is 1.02%, which barely exceeds the allowed limit. The short-range shots are the primary contributor to failures, with a nearly 2% UXO rate (three or four times that of the shots at medium and long range). However, the ally's Operational Mission Profile (OMP) calls for infrequent (7.5%) shots at short range, with the bulk at intermediate range (70%). Other systems can engage targets at the shorter ranges, so the current proposal is to restrict usage to above 25 km. The maximum range will also be reduced somewhat. Rocket velocity at the time of dispersal is believed

to be a contributor to fuze failure, and these changes eliminate the higher velocity dispersals, as will be discussed in the next section.

The impact of temperature on performance is less clear. Overall, UXO rates for the missions at medium and at long range were below 1%. However, the long-range rockets at ambient temperature had 13 failures among 997 submunitions—a 1.3% failure rate (higher than the 1% threshold with 80% confidence). Long-range rockets at cold temperature showed no failures (lower than the 1% threshold with 99.99% confidence). This performance indicates that the temperature does matter and that the rockets must be tested at various temperatures to ensure functionality “across the operating environment.”

At medium range, there is no apparent effect due to temperature, although this finding is obscured by the inability to separate submunitions from two of the shots. (Note that the merged data from the hot and ambient medium-range shots that were separately scored (1 failure in 996) do not appear consistent with the data from the rockets that impacted together (9 failures in 993 shots)). At short range, there is no ability to tease out temperature dependence, since the rockets all impacted in the same area.

Two conclusions—applicable to the employment and the testing of this system, respectively—can be drawn from these data. First, it can be concluded with 99.9+% confidence that the UXO rate on short shots exceeds 1%. Short-range use will need to be restricted. Second, it can be concluded from the long-range shots that temperature is a factor that must be considered.

These results led to a proposal from our ally for an extensive test and a reduced employment envelope (longer minimum range and shorter maximum range) for use of the munitions. The details of this proposal and the considerations in determining the passing criteria are discussed in the next section.

Proposed Extensive Testing of SDF

The basic steps in putting this test together are as follows:

- Identify the operational factors to be considered,
- Specify the extent of the test, and
- Decide on the “passing” criteria.

The factors that are considered in these tests to determine effectiveness are the temperature conditioning of the round and the range to target. Temperature conditioning is a standard feature of munitions testing, and evidence from the 2013 testing suggests that the temperature does matter for the longest range shots. Thus, hot, cold, and ambient shots will be included.

The evidence from the 2013 testing for an effect due to range is also compelling. The short-range shots clearly produce more UXO (38/1,993) than either medium-range (10/1,989) or long-range (13/1,987) shots. The superiority of the medium- range shots to the long-range shots is statistically marginal. The UXO rate correlates to the speed of the rocket at the time of expulsion, which is shown in Figure 3 as a function of range to

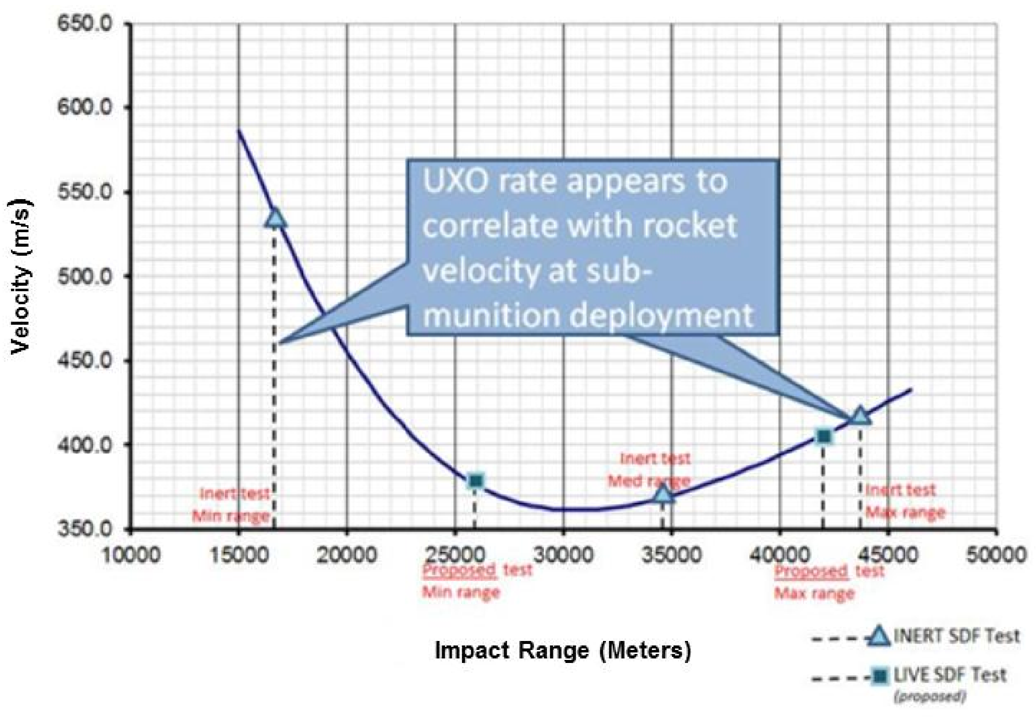

Figure 3. Rocket Velocity at Warhead Expulsion

target. In Figure 3, the dashed lines topped by an arrow indicate the 2013 test ranges, and the dashed lines topped by a square indicate the proposed ranges for the future test.

For artillery-shell-delivered submunitions, damage by collision following expulsion has been identified as a source of fuze failure.[1] The combination of successful earlier medium-range shots, along with a credible engineering explanation of why these shots performed best, suggests that testing at the medium ranges in addition to the proposed short- and long-range testing is unnecessary. As mentioned previously, the proposed minimum and maximum ranges for employment of the rockets are adjusted so that the submunition expulsion velocity is decreased. Based on the test results and engineering assessments, the minimum range for the rockets is increased from 16.8 to 26 km, and the maximum range is decreased from 43.8 to 42 km. Intended use of the system is at ranges of 30 km and beyond. The OMP is thus modified to have a 26-km minimum range (one of the ranges to be tested). Therefore, we have six "bins" (two ranges by three temperatures) to test, in contrast to the 2013 test, which had nine potential conditions (three ranges by three temperatures, five of which were distinguished in the testing).

These operational factors are to be explored in a much more extensive test in which 54 rockets rather than 12 rockets will be used. The increased number of rockets, coupled with the decreased number of bins to explore, leads to a more precise determination of UXO rate than was possible in the previous test.

1 Another possible source of fuze failure is damage to the fuze of one submunition when a different submunition detonates on dispersal, which is why live submunitions are required for the proposed test.

Many terminologies are used for discussing the precision of a determination of this type. The testing process is a sampling of a large population to determine one or more characteristics. The larger the sample, the more precise the determination. In this case, the intent is to determine whether a system meets a threshold for performance (less than 1% UXO). There is a “true” value of the UXO for the entire population of submunitions and an “observed” or “tested” value. The hope is that the true and observed values will either both pass or both fail the threshold; however, for any size test, there will be some possibility of error of either of two types:

- The system meets spec but fails the test (“producer risk”), or
- The system fails to meet spec but passes the test (“consumer risk”).

Expanding the scope of the test reduces the probability of error of either type, no matter what the true performance value is.

In addition to reducing the probability of an error, the “risk” can be shifted from the consumer to the producer by imposing a requirement that test results establish a confidence of greater than 50% that the system has met or exceeded the performance requirement. In general, this condition means requiring performance in the test that is better than the point estimate associated with the requirement.

For systems that just barely miss or just barely meet spec, the consumer’s risk is approximately one minus the required confidence level, and the producer’s risk is approximately the required confidence level. As the true performance exceeds or misses the required performance by greater amounts, the risk declines since it becomes more and more unlikely that the test results will lead to an incorrect conclusion.

This use of “risk” is essentially as a probability and differs from the acquisition use in which risk is a probability associated with a consequence. If risk is thought about as incorporating the severity of the consequence, the advantage of a more extensive test is not just that the probability of error decreases, but also that the probability of a large error collapses. This concept is illustrated later in the paper.

With 54 rockets (each carrying 504 submunitions) and six categories for the temperature and range factors, there are 9 rockets (4,536 submunitions) in each bin. Thus, 45 or fewer unexploded submunitions in each bin would establish a point estimate for each condition tested of 1% or less for the UXO. Since the measurements are randomly sampling a population, the point estimate is the value for which there is an approximately 50-50 chance of the entire population being either above or below the estimate. Requiring a more stringent threshold gives measurable confidence that the UXO rate is below 1%. Table 2 lists the confidence levels under consideration and the maximum number of UXO allowed.

Returning to the discussion of consumer’s and producer’s risk with a quantitative example of how consumer’s risk “collapses,” Table 3 compares the 9-rocket case to a 1+ rocket case. (For the 1+ rockets case, the number of submunitions was adjusted so the confidence levels can be matched at integer thresholds.)

Table 2. Confidence Levels under Consideration and Maximum Number of UXO Allowed

Nominal Confidence Level Required	Maximum Number of UXO from 9 Rockets (4,536 Submunitions)	Confidence Level Established*
Point estimate	45	48.2%
80%	39	80.8%
90%	36	91.0%

* This is the probability of exceeding the "Maximum Number" if the actual UXO rate were 1%.

Table 3. Consumer's Risk for Two Tests with 80% Confidence Thresholds

Number of Submunitions	Confidence Level/ UXO Threshold	Consumer's Risk If True UXO Rate Is 1.01%	Consumer's Risk If True UXO Rate Is 1.25%
557 (1+ rockets)	80.8%/3 UXO	18.6%	8.2%
4,536 (9 rockets)	80.8%/39 UXO	17.5%	0.80%

The consumer's risk when the UXO rate is 1.01% (1% above spec) is about the same in both cases but becomes negligible for the 9-rocket case if the UXO rate rises to 1.25% (the spec is missed by 25%).

It was noted previously that requiring confidence levels showing that the spec has been met is how the consumer can reduce his risk, but the risk is then shifted to the producer. The producer reduces risk by designing margin into the system. Again, an extensive test helps. If the producer successfully executes a design for 0.75% fuze failure, there is still a 60% probability that the system will fail a 1-rocket test with an 80% confidence requirement. However, this probability of failure drops to only 17% in the 9-rocket test, again with the 80% confidence required.

Conclusion

The proposal for a 54-rocket test explores the effects of temperature conditioning and range on the UXO rate for the submunitions. This extensive testing reduces the probability of sampling uncertainty, leading to an erroneous conclusion. In addition, the use of an 80% confidence requirement on this extensive test essentially eliminates any possibility of passing the fuze if the failure rate is appreciably about the 1% threshold. There is no prospect for large errors of this type. Further, because of the extent of the test, a reasonable design margin allows the producer to reduce the risk of an erroneous adverse result to a tolerable level.

Abbreviations

CBU	Cluster Bomb Unit
DT&E	Developmental Test & Evaluation
FMS	Foreign Military Sales
MLA	manufacturing license agreement
OMP	Operational Mission Profile
OSD	Office of the Secretary of Defense

SDF	self-destruct fuze
SFW	Sensor Fuzed Weapon
TWS	Tactical Warfare Systems
UXO	unexploded ordnance
WSMR	White Sands Missile Range

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